Safety and accuracy of minimally invasive long bone fracture repair using a 2.5-mm interlocking nail: a cadaveric feline study

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Abstract: OBJECTIVES: The Targon Vet System (TVS) is a 2.5-mm interlocking nail that can be applied minimally invasively. The purpose of this study was to test if the TVS could be safely applied percutaneously to different feline long bones without fluoroscopic guidance. METHODS: A gap fracture was created in 96 feline humeri, femora and tibiae (n = 32/group). Paired bones were randomly assigned to two treatment groups: (1) TVS inserted percutaneously with fluoroscopy and (2) TVS inserted percutaneously without fluoroscopy. Intraoperative evaluation (complications, procedure time, attempts), radiographs (pre-/postoperative alignment, length) and anatomical dissection (neurovascular injury, rotational alignment) were compared between treatment groups. RESULTS: The use of fluoroscopy did not lead to significant differences in any of the outcome measures. Intraoperative complications predominantly occurred in the distal humerus (12/32) and the proximal femur (7/32). In total, 20/96 complications occurred with no complications for the tibia. Neurovascular structures were only damaged at the medial side of the distal humerus (10/32). CLINICAL SIGNIFICANCE: We conclude that the TVS can be safely applied percutaneously to the tibia and with limitations to the femur in normal cadaveric cats without fluoroscopy. Despite the limitations of a cadaveric study, the high number of complications is leading us to consider the humerus not safe for the TVS. A learning curve has to be expected and technical recommendations should be respected to decrease complications.

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Safety and Accuracy of Minimally Invasive Long Bone Fracture Repair Using a 2.5-mm Interlocking Nail: A Cadaveric Feline Study

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Abstract

Objectives The Targon Vet System (TVS) is a 2.5-mm interlocking nail that can be applied minimally invasively. The purpose of this study was to test if the TVS could be safely applied percutaneously to different feline long bones without fluoroscopic guidance.

Methods A gap fracture was created in 96 feline humeri, femora and tibiae ($n = 32$/group). Paired bones were randomly assigned to two treatment groups: (1) TVS inserted percutaneously with fluoroscopy and (2) TVS inserted percutaneously without fluoroscopy. Intraoperative evaluation (complications, procedure time, attempts), radiographs (pre-/postoperative alignment, length) and anatomical dissection (neurovascular injury, rotational alignment) were compared between treatment groups.

Results The use of fluoroscopy did not lead to significant differences in any of the outcome measures. Intraoperative complications predominantly occurred in the distal humerus (12/32) and the proximal femur (7/32). In total, 20/96 complications occurred with no complications for the tibia. Neurovascular structures were only damaged at the medial side of the distal humerus (10/32).

Clinical Significance We conclude that the TVS can be safely applied percutaneously to the tibia and with limitations to the femur in normal cadaveric cats without fluoroscopy. Despite the limitations of a cadaveric study, the high number of complications is leading us to consider the humerus not safe for the TVS. A learning curve has to be expected and technical recommendations should be respected to decrease complications.

Keywords
- ► interlocking nail
- ► minimally invasive fracture repair
- ► fluoroscopy
- ► safety and accuracy
- ► cat

Introduction

Comminuted diaphyseal long-bone fractures are a common sequel of high energy trauma in cats.[1,2] Reported treatments of comminuted fractures in dogs and cats include external fixation, plate alone or a combination of an intramedullary pin or interlocking nail with plate.[3] Over the past two decades, traditional fixations methods of open anatomic reduction and internal fixation shifted toward minimally invasive osteosynthesis techniques.[4–7] Minimally invasive osteosynthesis (MIO) may be particularly advantageous when treating comminuted long-bone fractures because the preservation of the soft tissue envelope around the fracture promotes rapid fracture healing and decreases the risk of implant failure and post-surgical infection.[6] The biological advantage of MIO is particularly relevant when treating fractures at risk of non-union, such as feline tibial fractures. These fractures may be predisposed to healing disturbances because of limited soft

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tissue coverage.[8,9] Therefore, MIO may help preserve the minimal soft tissue and thereby decrease the risk of fracture healing complications in cats.

A suitable fixation method for biological osteosynthesis of comminuted fractures is the interlocking nail. This fixation method can be applied minimally invasively while providing the required mechanical stability in comminuted fractures, a common indication for MIO.[10–13] The mechanical advantages of interlocking nails result from being positioned in the neutral axis of the bone and from its relatively big area moment of inertia.[11,14,15] Good clinical results have been reported with the use of standard interlocking nails for the management of humeral, femoral and tibial fractures in cats and dogs.[10,16–19] However, up to 12% of feline and canine diaphyseal fractures treated with standard interlocking nails had to be revised with supplemental fixation to eliminate perioperative instability and thereby preventing delayed union, non-union and construct failure.[16,18,20]

The Targon Vet System (TVS) (Targon VET; B. Braun Vet Care GmbH, Tuttlingen, Germany) is a recently developed angle stable interlocking nail utilizing a new mechanism of bolt fixation.[21,22] Initial clinical experience is promising.[23] First, a single threaded cannulated locking bolt is inserted in each fragment, and then a relatively small intramedullary pin is advanced through the bolts cannulation and locked with a fixation screw. This unique system allows correction of rotational alignment after implantation of the locking bolts. This feature might be a significant advantage for MIO, because rotational malalignment has been described as a major complication in people who have a fracture being treated by MIO using interlocking nail.[24] Fluoroscopy allows evaluation of limb alignment intraoperatively when performing MIO.[25,26] However, it is unclear if fluoroscopy is always necessary when performing MIO. Finding strategies to limit the use of fluoroscopy during MIO has clear advantages on safety.[27–29] The purpose of this study was to test if the TVS could be safely applied percutaneously without fluoroscopic guidance in a feline cadaveric gap fracture model. We hypothesized that (1) TVS could be safely applied with MIO technique with or without fluoroscopy to humeral, femoral and tibial fractures simulated in a feline cadaver model; (2) there would be no difference in surgical time, intraoperative complications and fracture alignment between bones fixated using fluoroscopy and without fluoroscopy.

Materials and Methods

Study Design

The cadavers of 32 skeletally mature domestic shorthair cats were collected. The cats weighed between 4 and 6 kg, showed no signs of musculoskeletal disease on physical examination or any disease affecting bone quality based on medical records and were euthanatized for reasons unrelated to this study. The cadavers were used according to the institution policy on use of biological tissue for research and a written owner consent form was signed by the owner. The feline cadavers were frozen in sealed plastic bags and stored at −18°C. Preoperative radiographs of both humeri, femora and tibiae were taken to exclude overt pre-existing bone diseases and to perform preoperative measurements.

Two board certified surgeons (AP, SCK) each performed a total of 48 TVS nail placements in the humeri, femora and tibia of eight cats. The paired bones of these cats were randomly assigned to two treatment groups: (1) TVS inserted percutaneously under fluoroscopy guidance (fluoroscopy); (2) TVS inserted percutaneously without fluoroscopy (no fluoroscopy). A randomized block design was used to normalize for side of the bone (left or right) for each group and bones. In summary, each of the two treatment groups consisted of 16 humeri, 16 femora and 16 tibiae (8 left, 8 right sides each) that underwent nail placement performed by two surgeons.

Cadaver Preparation

The feline cadavers were thawed to room temperature 24 hours prior to testing. To simulate a comminuted fracture, a 10 mm mid-diaphyseal gap was created in each of the tested bones. For this purpose, medial approaches of ∼20 mm in length were performed to expose the mid diaphysis of each bone. To enable postoperative assessment of rotational alignment, 1 mm deep, longitudinal notches extending ∼5 mm over the fracture site were sawed into the bones and highlighted with a black permanent marker. A 10-mm gap was created using an oscillating saw. The approaches were closed using a simple continuous suture pattern.

Surgical Procedure

For all of the procedures, the 2.5 mm intramedullary nail was used. The length of the locking bolts was selected based on the measurement of the depth gauge at the drill hole. The sizes ranged from 16 to 24 mm. The part of the locking bolt which was anchored in the trans-cortex had a self-tapping thread with outer diameter of 2.8 mm, a core diameter of 2.2 mm and a thread pitch of 1.2 mm. The thicker part of the locking bolt, placed in the medullary cavity and in the cis-cortex, had an outer thread of 4.8 mm with a thread pitch of 1.2 mm and was hollow to engage the fixing screw that had a diameter of 3 mm.[21]

Radiographic Planning

Radiographs were calibrated and measurements were made by 1 person (KN). The lengths of all tibiae, femora and humeri were measured on mediolateral radiographs. The tibial length was measured from the tibial intercondylar eminence to the most proximal aspect of the talocrural joint. The femoral length was obtained from the most proximal aspect of the greater trochanter to the most distal aspect of the lateral femoral condyle. The humeral length was measured using the proximal aspect of the greater tubercle and the distal aspect of the lateral humeral condyle as landmarks. These measurements were used intraoperatively to adjust for length after placing the TVS nail. Additional measurements of the outer bone diameter were taken on mediolateral radiographs to define a proximal and a distal corridor in the metaphyseal region for safe locking bolt insertion. Safe insertion of the bolts was considered where the bone diameter was at least 8.5 mm.[21] Otherwise the position with the widest possible outer bone diameter in the metaphyseal region was selected. In the distal tibia, the centre of the bolt was placed at a minimal distance of 5 mm (approximate locking bolt diameter) from the talocrural joint to allow sufficient advancement of the nail through the locking bolt and locking of the nail. To avoid placement of the locking bolt into the supracondylar foramen of the humerus, the distal humerus safe corridor was defined at a minimal distance of ~5 mm proximal to the supracondylar foramen.

Tibia

Cats were positioned in dorsal recumbency and the medial surface of the crus was exposed. A 20 to 30 mm skin incision was made along the distal medial border of the patellar ligament and the proximal tibia and a MIO approach to the proximal tibia was performed. In the first four cases of surgeon A (SCK), both locking bolts were placed at first and then the nail was inserted as recommended by the manufacturer. To facilitate the alignment of the locking bolts with the nail, we decided to slightly modify the procedure after the first four cases, by inserting the nail at first and afterwards the bolts as described below.

A pilot hole was initiated immediately cranial to the intermeniscal ligament, using a 2.0-mm drill bit directed along the medullary canal. Then a 2.5-mm nail was inserted into the proximal tibial fragment and used to guide the proximal locking bolt placement in alignment with the nail and the bone. Typically, the proximal bolts were positioned approximately 5 to 10 mm below the level of the tibial tuberosity, based on the preoperative planning. Before drilling the bolt hole, the nail was retracted to avoid interference. A tissue protection sleeve was used to drill the cis-cortex with a 4.0-mm drill bit. Then, a drill sleeve was inserted into the 4.0 mm diameter hole and the trans-cortex was drilled using a 2.0-mm drill bit. The depth of the drilled hole was measured with the depth gauge and a corresponding locking bolt was selected and inserted, after tapping the hole in the cis-cortex. The nail was reinserted and pushed through the locking bolt. If this was not possible, the bolt was rotated clockwise or counterclockwise until the cannulation was aligned and the nail could be pushed through. In some cases, a 1.8 mm Kirschner wire was used to estimate the position of the cannulation before inserting the nail. In the treatment group 'fluoroscopy', orthogonal fluoroscopic views were used to locate the bolt in relation to the nail if necessary (►**Fig. 1A**). Correct advancement through the cannulation was confirmed if the bolt was engaged and could not be rotated. The distal medial cortex was exposed through a 10 to 20 mm skin incision right above the malleolus. The typical location for the distal bolt was approximately 5 to 10 mm above the talocrural joint to avoid penetrating into the joint. The bolt was implanted as described above for the proximal bolt and the nail subsequently pushed through the oblong cannulation of the distal locking bolt. Advancement was confirmed by rotating the bolt carefully.

The surgeon evaluated proper rotational alignment by flexing and extending the stifle and tarsal joint, while observing the alignment of the tibial crest, the femoral condyles, the malleoli and the metatarsi. The preoperative bone length was re-established by measuring and adjusting the length of the fixed tibia. In the 'fluoroscopy' treatment group, an additional verification of tibial alignment was performed using fluoroscopy. Once rotational alignment and bone length were deemed to be correct, the fixation screws were inserted and tightened at a torque of 1.4 Nm.

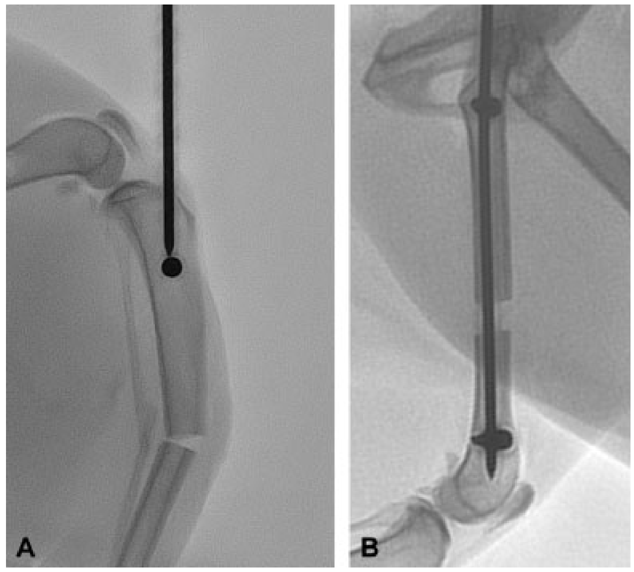

Fig. 1 (**A**) Example of a fluoroscopic image showing the position of the nail in relation to the locking bolt and the proximal tibial fragment. (**B**) Intraoperative fluoroscopic image of a femur ('fluoroscopy' treatment group) to recheck implant position and alignment.

Femur

Cats were positioned in lateral recumbency to enable a lateral MIO approach to the feline femur.[7] The TVS insertion in the femur was performed according to the description of the tibia. Attempts were made to insert the nail at the craniolateral aspect of the trochanteric fossa. The proximal bolt was positioned in the area of the lesser trochanter and the distal bolt was positioned in the metaphysis of the distal femur proximal to the Blumensaat line (►**Fig. 1B**). Proper rotational alignment was obtained by assessing the position of the femoral head and neck in relation to the femoral condyles. Based on the surgeon's subjective estimation, the position of the femoral head and neck, which physiologically shows some degree of anteversion in the cat was determined by direct palpation through the proximal MIO incision and adjusted when indicated.

Humerus

Cats were positioned in lateral recumbency and a lateral MIO approach to the feline humerus was performed. The TVS insertion in the humerus was performed according to the description of the tibia. The nail was inserted at the greater tubercle and directed slightly caudomedial. The proximal bolt of the humerus was typically located in the area of the distal aspect of the lesser tubercle. The results of pilot testing indicated the medullary cavity in the area of the distal humeral metaphysis to be too narrow for safe nail insertion. In addition, bolt placement through the supracondylar foramen had to be avoided. Therefore, the distal bolt was positioned proximal to the supracondylar foramen, in the area where the brachialis muscle and the radial nerve cross the humerus. The radial nerve was identified through the distal incision and retracted during the surgical procedure to assure integrity of the nerve. Rotational alignment was obtained by assessing the position of the greater and lesser trochanter in relation to the humeral epicondyles as well as assessing range of motion of the elbow.

Outcome measures

Radiographs

Orthogonal radiographs of the bilateral tibiae, femora and humeri were obtained pre- and postoperatively for each animal. Limb alignment and bone length were measured in degrees and mm, respectively. Joint reference angles were measured using the methods previously described for cats and dogs (►**Fig. 2A–D**).[30,31] Tibial varus/valgus angulation was computed as (mechanical medial proximal tibial angle + mechanical medial distal tibial angle – 180 (►**Fig. 2A**, **C**)) and femoral varus/valgus angulation as (mechanical lateral proximal femoral angle + mechanical medial distal femoral angle – 180). For humeri, only mechanical lateral distal humeral angle (mLDHA) was used. The difference between pre- and postoperative measures of bone length and joint reference angles in the frontal plane were used to compare the accuracy of fracture reduction between treatment groups. A difference of less than 10° between pre- and postoperative measurements was considered acceptable. This value was selected based on clinical experience.

The postoperative radiographic evaluation additionally included the measurement of the fracture gap in mm, the outer diameter of the bone (mediolateral views) and the diameter of the medullary canal (craniocaudal views) at the bolt insertion site. The radiographs were reviewed to detect fractures or fissures as well as to evaluate implant position. Acceptable position of the TVS was considered if the locking bolts were in the preoperatively determined corridor and the nail was passed through the cannulation of the locking bolts.

Intraoperative Evaluation

The time of the procedure was measured starting with the first incision and stopped after successful implant placement based on the surgeon's intraoperative subjective assessment. The numbers of attempts needed for successful insertion of the pin into the medullary cavity and through the oblong cannulation of the bolt were recorded. Intraoperative complications such as fissures, fractures or complete cortex perforations were recorded if noted and evaluated for the severity of sequelae (minor or major complication). A distinction was made between cases that would require a cerclage but not revision of the nail (minor complication) and those cases where the fracture would require nail

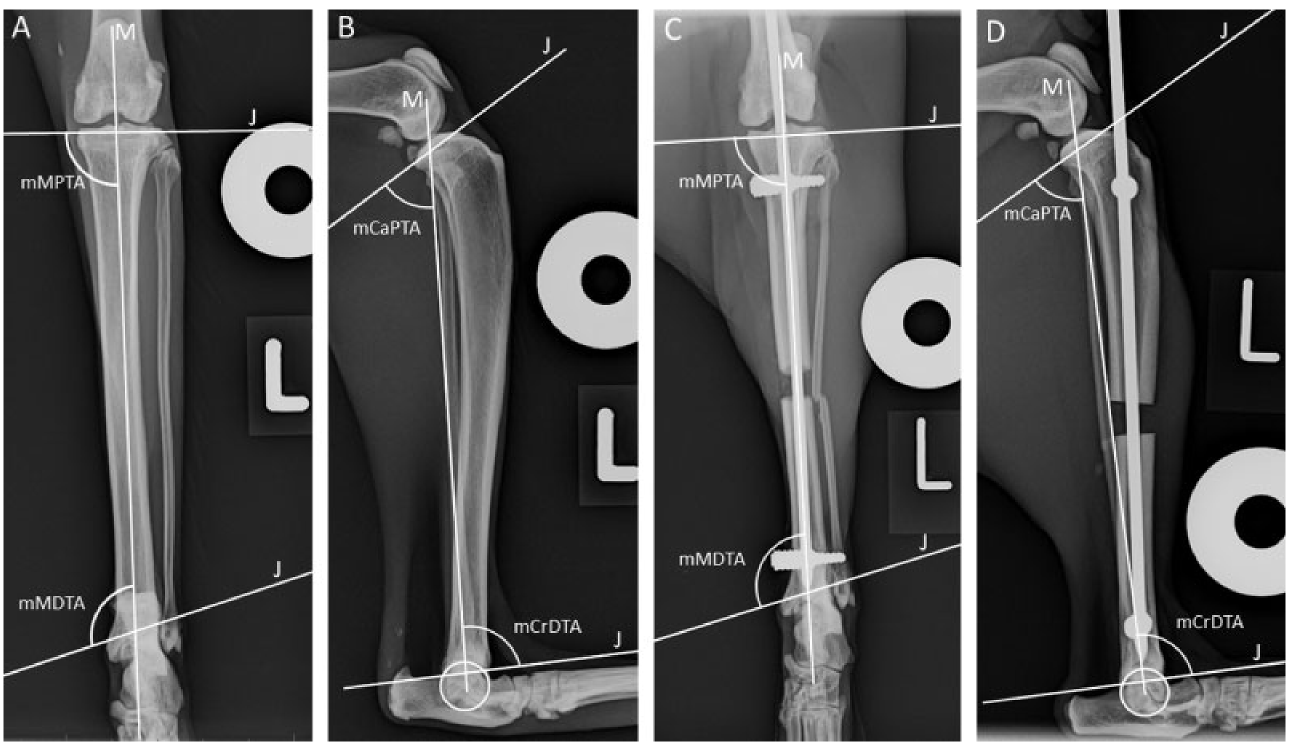

Fig. 2 Pre- and postoperative radiographic projections of the left tibia of a cat used in this study. The intersection of the mechanical axes (M) and the joint orientation lines (J) form the mechanical joint reference angles. (**A**) Preoperative measurements of the mechanical medial proximal tibial angle (mMPTA) and the mechanical medial distal tibial angle (mMDTA) in the frontal plane. (**B**) Preoperative measurements of the mechanical caudal proximal tibial angle (mCaPTA) and mechanical cranial distal tibial angle (mCrDTA) in the sagittal plane. (**C**) Postoperative measurements of the mMPTA and mMDTA in the frontal plane. (**D**) Postoperative measurements of the mCaPTA and mCrDTA in the sagittal plane.

removal and an alternative fixation system (major complication).

Anatomical Dissection

After obtaining the postoperative radiographs, the limbs were carefully dissected to assess the integrity of the major regional neurovascular structures. After exposing the fracture gap, rotational alignment was estimated by measuring the rotational shift (RS) of the longitudinal periosteal notches done preoperatively. The distance between the proximal and distal longitudinal marking was measured perpendicular to the long axis (RS) as well as the circumference of the bone (CB). Then these linear measurements were converted into degree of rotational malalignment (R°) with ([RSmm*360°]/CBmm = R°). Rotational malalignment less than 15° was considered acceptable based on clinical experience.

Data Analysis

Statistical analysis was performed using commercially available software (SPSS 22.0; IBM Corp., Armonk, New York, United States; R Development Core Team (2016) R: A Language and Environment for Statistical Computing, Vienna, Austria). For the continuous parameters, means ± standard deviation were calculated for each parameter per group. Outcome measures (frontal alignment, rotational alignment, bone length, attempts to hit bolt hole, time of procedure) were compared between the two groups with or without fluoroscopy and between the bones (humerus, femur and tibia) using linear mixed models.

For the qualitative parameters 'complications' and 'incidence of neurovascular injury', median and interquartile range (IQR, 25th–75th percentile) was calculated. Fisher's exact test was used to compare between the groups with or without fluoroscopy and between the bones.

The relationship between outer bone diameter or medullary canal diameter of the distal humerus and the occurrence of intraoperative complications (fissures and fractures) was analysed using a Spearman Correlation.

The Benjamini–Hochberg procedure was used to correct for multiple comparisons. The level of significance was set at $p < 0.05$.

Results

Two surgeons performed percutaneous application of the TVS in 96 bones, including 32 tibiae, 32 femora and 32 humeri (►**Supplementary Appendix Table 1**, available in online version only). The use of fluoroscopy did not lead to significant differences in any of the outcome measures (►**Fig. 3A–E**, ►**Table 1**).

When the three different bones were compared with each other, the time of the procedure for the tibia (13.5 min ± 4) was significantly shorter than for the femur (19.5min ± 7.5) and the humerus (18.8 min ± 3.7) (►**Fig. 3E**). Other significant differences among bones included better frontal alignment of the tibia relative to the femur and humerus and significantly more attempts needed to insert the nail through the locking bolt in the femur compared with the humerus and tibia (►**Fig. 3A, D**).

Complications

Intraoperative complications predominantly occurred in the distal humerus (12/32, ►**Fig. 4**) and the proximal femur (7/32, ►**Fig. 5**). When all bones were pooled together, 20/96 complications occurred, including 10 majors (all fractures) and 10 minors (7 fissures and 3 cortex perforations). In the humerus, six major (all distal) and seven minor (all distal except one cortex perforation proximally) complications occurred, whereas in the femur four major and three minor complications occurred, all being proximal. No complications occurred in the tibia which is significantly less than in the humerus with a complications rate of 13/32. All except one of the complications in the femur resulted from the first eight femoral TVS applications (first 4 out of 8 cadavers) the surgeons had performed, whereas in the humerus complications were not associated with the initial learning curve.

A strong correlation (correlation coefficient $r = -0.6374$) was found between intraoperative complications (fissures and fractures) and medullary canal diameter in the distal humerus (►**Fig. 6**, ►**Supplementary Appendix Table 1**, available inonline version only). In 5/6 of the cases with major complications (fractures) in the distal humerus, the medullary canal diameter (3.6 mm [3.5–3.7]) was smaller than 4 mm. The 4 mm is the length of the part of the bolt (with the cannulation for the nail) that is supposed to sit in the medullary canal (►**Fig. 7**). On the other hand, in 19/20 of the repaired humeri without complications the medullary canal diameter was bigger than 4 mm (4.55 mm [4.4–5]).

Percutaneous technique could be used in all of the TVS applications. However, in 10/32 of the treated humeri, dissection revealed neurovascular damage at the medial humerus where the distal locking bolt protruded from the trans-cortex (►**Fig. 8**). In seven cases, the median nerve and the brachial vessels were wrapped around the bolt tip, in one case only the median nerve was injured and in two cases only the brachial vessels were involved. Percutaneous TVS application in tibiae and femora did not lead to visible neurovascular damage which is significantly less than the 10/32 incidences of neurovascular damage in the humerus.

When intraoperative complications and postoperatively detected incidences of neurovascular damage were pooled together an overall complication rate of 23/32 in the humerus, 7/32 in the femur and 0/32 in the tibia was found.

Postoperative Assessment

Restoration of preoperative bone length, acceptable implant position as well as acceptable sagittal and frontal alignment was achieved in all bones. However, the difference between pre- and postoperative frontal alignment was significantly less in the tibia than in the femur and the humerus (►**Fig. 3A**, ►**Table 1**). Rotational malalignment was greater than 15° in 11/84 of the cases (6 with fluoroscopy and 5 without fluoroscopy, ►**Fig. 3B**). Palpation was found useful even in the fluoroscopy group especially when evaluating rotational alignment.

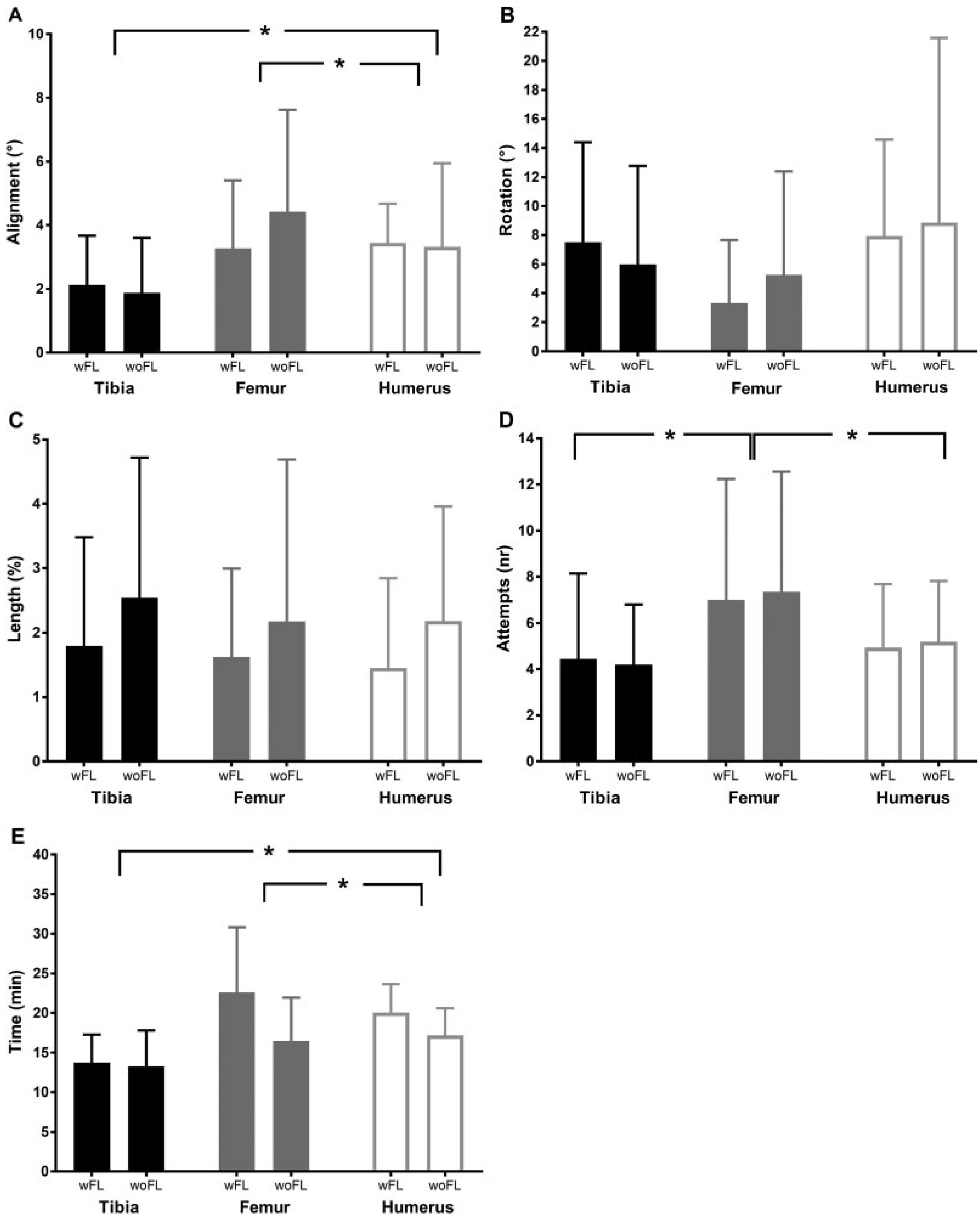

Fig. 3 (**A**) Difference between pre- and postoperative measures of frontal limb alignment, (**B**) postoperative measured rotation, (**C**) difference between pre- and postoperative measures of bone length, (**D**) attempts needed for successful insertion of the pin through the bolt and (**E**) procedure time for 32 humeri, 32 femora and 32 tibiae that received percutaneous application of the Targon Vet System with (wFL) or without (woFL) fluoroscopic guidance. *Indicates significant difference between bones.

Table 1 Mean ± SD for outcome measures (alignment, rotational malalignment, bone length, attempts to hit bolt hole and time of procedure) for the 32 tibiae, femora and humeri and corresponding *p*-values

Outcome measures	Tibia	Femur	Humerus	Without vs. with fluoro *p*-value	Tibia vs. femur *p*-value	Tibia vs. humers *p*-value	Femur vs. humerus *p*-value
Alignment (varus/valgus°)	2 ± 1.6	3.8 ± 2.7	3.4 ± 1.9	1.104	0.010[a]	0.018[a]	0.839
Rotational malalignment (°)	6.7 ± 6.8	4.3 ± 5.9	8.3 ± 9.6	1.114	0.285	0.314	0.348
Difference in bone length (%)	2.2 ± 2	1.9 ± 2	1.8 ± 1.6	0.345	0.874	0.918	0.966
Attempts to hit bolt hole (*n*)	4.3 ± 3.2	7.2 ± 5.1	5.0 ± 2.7	0.995	0.012[a]	0.971	0.008[a]
Time of procedure (min)	13.5 ± 4	19.5 ± 7.5	18.8 ± 3.7	0.054	0.001[a]	0.003[a]	0.88
Complications (nr)	0	7	13	0.802	0.078	0.002[a]	0.177
Neurovascular injury (nr)	0	0	10	0.999	1	0.000[a]	0.000[a]

Abbreviation: SD, standard deviation.
Note: Complications and neurovascular injuries are listed as absolute numbers out of all the cases.
[a]A value of $p < 0.05$ was considered significant.

Discussion

This cadaveric study documented the percutaneous application of a 2.5 mm diameter TVS with and without fluoroscopic guidance to different feline long bones. In agreement with our first hypothesis, our results showed no difference in alignment, number of complications and surgical time using the TVS percutaneously with or without fluoroscopy. Our results should be interpreted carefully because a cadaveric model does not replicate the conditions of naturally occurring fractures including swelling and muscle contracture. Complications such as iatrogenic fractures, fissures and neurovascular trauma were commonly found when applying the TVS to the humerus. Therefore, we reject our second hypothesis and conclude that TVS is safe for the tibia and for the femur under certain conditions but should be further evaluated for the humerus.

In this study, TVS applications under fluoroscopic guidance did not lead to better outcome measures compared with the application without fluoroscopy. We suspect that

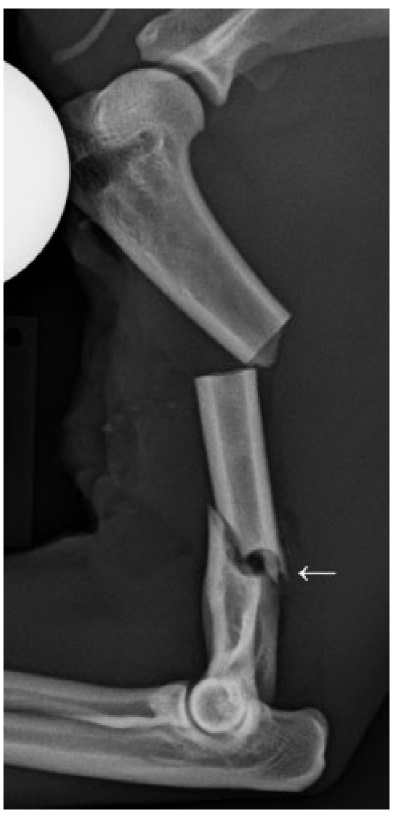

Fig. 4 Example of an iatrogenic fracture through the distal bolt hole (arrow) in a right humerus with a medullary canal diameter of 3.6 mm in the frontal plane.

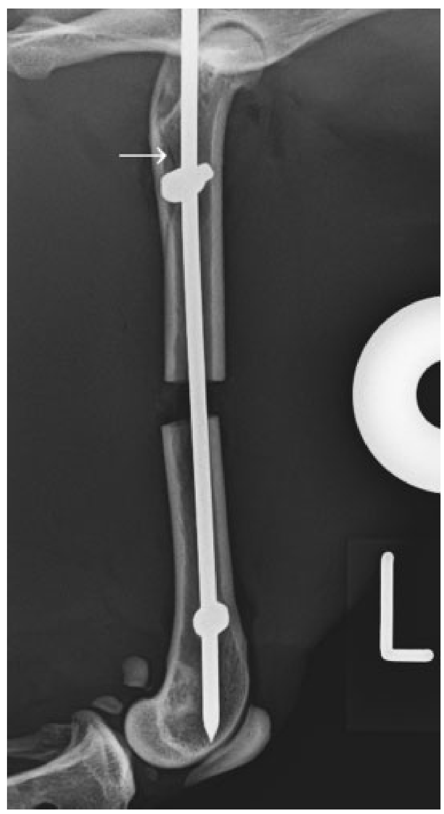

Fig. 5 Example of a fissure (arrow) through the proximal bolt hole in a left femur.

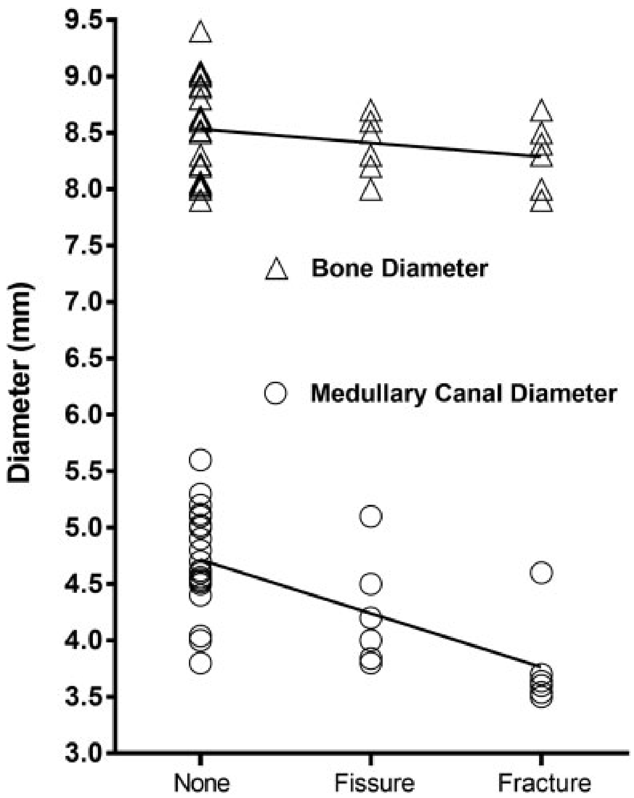

Fig. 6 Spearman correlation between complications (none, fissure or fracture) and bone diameter (above) and medullary canal diameter (below) in the distal humerus. The correlation between the type of complication and the bone diameter was not significant (above, $p = 0.1636$; $r = -0.2523$). A correlation coefficient of $r = -0.6374$ indicates a strong correlation between the type of complication and the medullary canal diameter (below). This correlation is significant ($p \leq 0.0001$). In the initial recommendations the bone diameter rather than the medullary canal diameter was considered relevant for safely placing a Targon Vet System into a bone.[25]

alignment was not influenced by the use of fluoroscopy because an interlocking nail effectively controls sagittal and frontal alignment, similarly to an intramedullary pin during minimally invasive plating.[32] Moreover, our results indicate that fluoroscopy was not beneficial for evaluating rotational alignment reliably. Palpation of anatomical landmarks while flexing and extending the proximal and distal joints was the preferred method to assess alignment. On the other hand, intraoperative fluoroscopy was found to be helpful when there were difficulties with the alignment of the nail with the locking bolt. It may be useful especially during the initial learning phase using the TVS in MIO technique. However, the benefits of intraoperative fluoroscopy should also be carefully weighed against potential safety concerns.[27–29] The frequent use of ionizing radiation may have long-term insidious health effects and therefore the fluoroscopic unit should only be used if the advantages clearly outweigh the disadvantages.[25]

The rate of iatrogenic fractures that we observed, especially in the humerus, is even higher than previously reported in a clinical study using the TVS.[23] The humerus had an intraoperative complication rate of 41%, comparably higher than in the femur (22%) and tibia (0%). In contrast to other systems where the nail diameter may be the cause of complications,[17,33] the increased risk of iatrogenic fractures in the humeral bone using the TVS may depend on the size and design of the locking bolts relative to the medullary diameter. The cannulation in the locking bolt and the cone-shaped part adjacent to it have a total length of 4 mm. Thus, a medullary diameter smaller than 4 mm does not allow sufficient insertion of the locking bolt without having a high risk for the creation of fissures and fractures in the trans-cortex (►**Fig. 7**). The occurrence of occult fractures in the trans-cortex may increase the risk of postoperative failures.

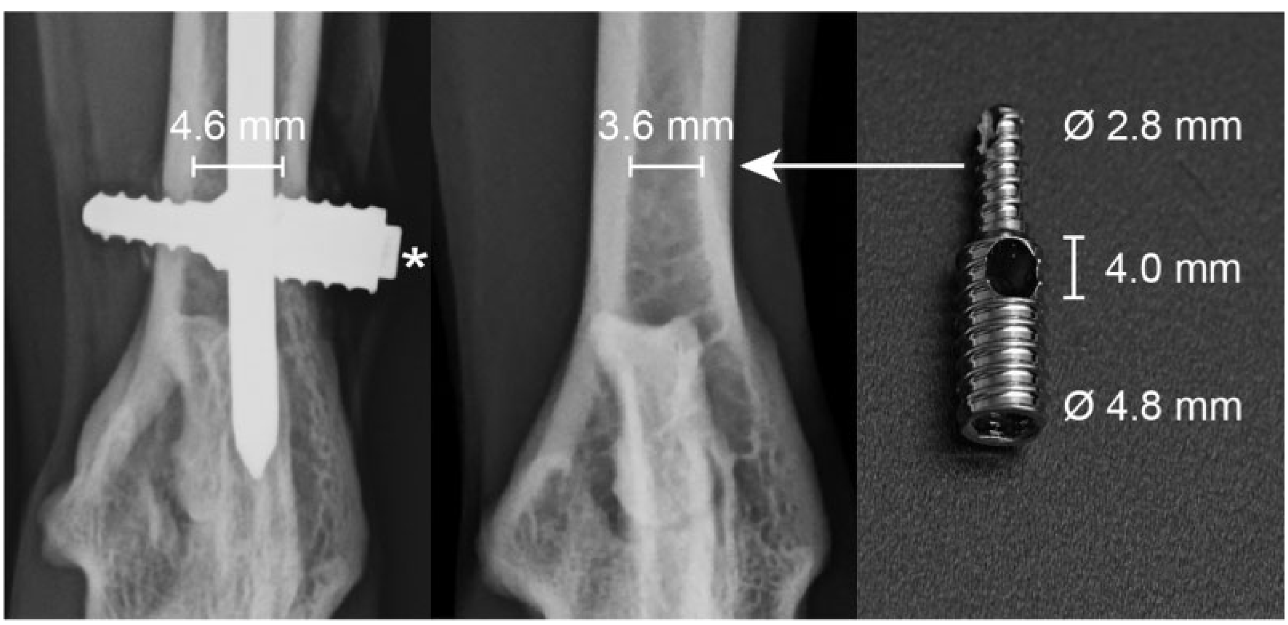

Fig. 7 This image shows a 16-mm long locking bolt on the right side and a left distal humerus in the middle and on the left side. A medullary canal diameter of 3.6 mm (middle) is too small for safe bolt insertion, whereas a medullary canal diameter of 4.6 mm (left side) allows the designated locking bolt insertion. The construct of the intramedullary nail and locking screw (left side) is locked with a small fixing screw (white asterisk).

The fractures and fissures that occurred in the femur were all located at the proximal drill hole but they were not associated with a specific medullary or bone diameter. The technical errors that led to these fractures are avoidable, especially following the initial learning curve.

In addition to the occurrence of humeral fractures and fissures, damage to the median nerve and the brachial vessels was discovered in 31% of the repaired humeri (►**Fig. 8**). This finding is unexpected because previous studies on interlocking nails in small animals reported radial nerve paralysis, radial neuropraxia and sciatic nerve damage but no injuries to the median nerve. However, these studies did not focus on cats and involve very few (11) cats with humeral fractures.[16–20,34]). Studies in humans demonstrated that not only the radial nerve but also the ulnar and median nerves as well as the brachial artery are at high risk with the application of the lateral to medal distal locking bolt.[35–37] In our study, damage to the radial nerve could be avoided by protecting the nerve under visual control. Although preoperative radiographic measurements were performed to prevent from drilling too close to the supracondylar foramen, damage to the median nerve and brachial vessels more proximally to the foramen could not be avoided in 31% cases. The risk of iatrogenic injuries to the median nerve has not been previously investigated in cats. However, a recent anatomical study on minimally invasive plate oteosynthesis (MIPO) in cats reported similar findings.[7] We suspect that inserting the locking bolt close to the supracondylar foramen may have increased the risk of median nerve damage because of lack of mobility of the nerve through the supracondylar foramen, specifically in cats. Guidelines to avoid implant positioning into the supracondylar foramen as previously published might help decreasing the risk for nerve damage.[33] Another potential way to avoid these complications can be achieved by a medial approach where the medial border of the supracondylar foramen is removed with a rongeur, thereby freeing the brachial artery and median nerve.[7]

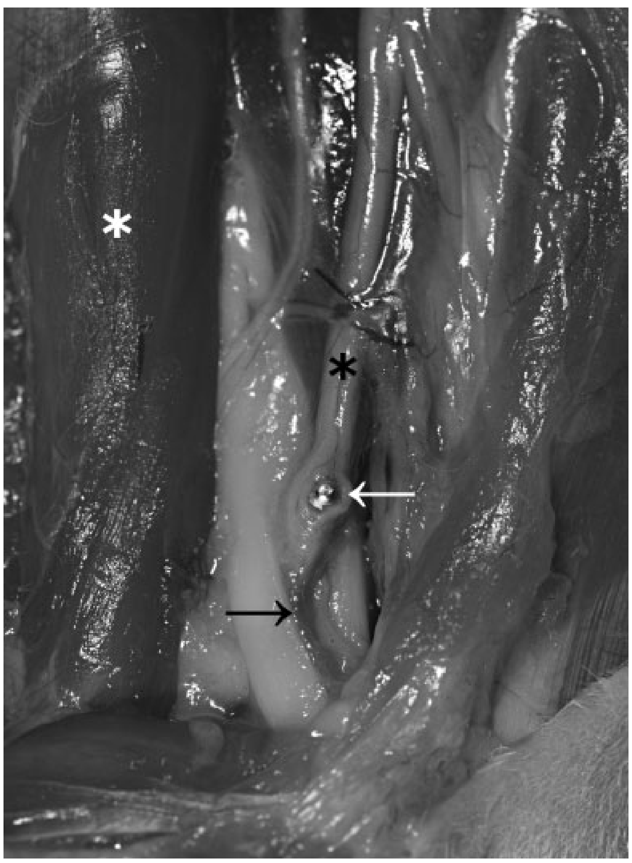

Fig. 8 Example of median nerve (black asterisk) damage after inserting the locking bolt (white arrow) in a lateromedial direction in a right distal humerus approximately 6 mm proximal to the supracondylar foramen. Note the median nerve and brachial vessels entering the supracondylar foramen (black arrow). The biceps brachii muscle is shown with the white asterisk.

The findings of this cadaveric study demonstrate the necessity of getting familiar with the application technique of the TVS before using it in clinical cases. Because of the tight fit between nail and cannulation in the bolt, it is crucial to position the bolt perpendicular to the nail course and the long axis of the bone. Thus, reaming or penetrating the cortex by advancing the nail can be avoided and the nail can be passed more easily. Especially in the proximal femur, the shape of the bone can lead to mistakes such as incorrect position of the bolt and poor insertion angle of the nail. Forcing the nail in a poorly positioned bolt may lead to fissures or fractures. Accordingly, we recommend to pay attention that the bolt is placed in the middle of the lateral aspect of the proximal femur to avoid this problem (►**Fig. 9**). We would advise to use bone-holding forceps through the incisions or percutaneously to make aligning of the fragments and insertion of the nail easier and to facilitate untroubled drilling.

Our findings do not support the recommendation of a minimally required outer bone diameter of 8.5 mm as measured in the sagittal plane for safe bolt insertion that was proposed in a previous study.[21] In our study we found that the medullary diameter in the frontal plane may be a more relevant parameter than the outer bone diameter, as observed in the humerus (►**Fig. 7**). The mechanism of fissure formation observed in our study was directly related to the size of the medullary canal that requires a minimal diameter necessary to position the cannulation of the bolt into the medullary canal. We found that the bolts that could not be inserted completely due to a small medullary canal diameter bone frequently caused fissures and fractures. The surgeon should be aware of this limitation especially when managing humeral fractures as the distal metaphysis has a significant narrower section.

In this study, bones with diameters smaller than 8.5 mm at bolt insertion site were not associated with a higher incidence of fractures or fissures than bones with diameters bigger than 8.5 mm. Whether the relatively large diameter of the locking bolts (►**Fig. 7**) would compromise the structural integrity of the diaphysis and therefore be a problem in clinical cases could not be determined from this cadaveric study.

The setup of this experimental cadaveric study entails several limitations. First of all, the cadaveric bone subjectively felt more brittle than what is found in clinical patients, which might have led to an overestimation of iatrogenic complications. On the other hand, fracture reduction might

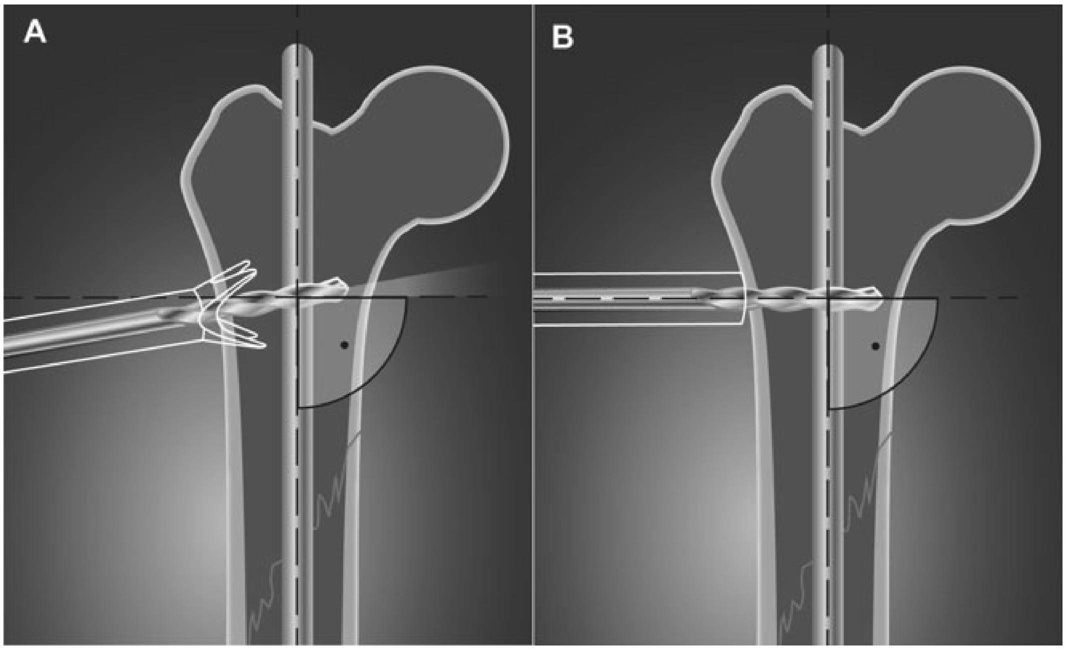

Fig. 9 Since the cortex of the metaphyseal bone is not parallel to the medullary canal the centring drill guide (A) could not be used to assure drilling perpendicular to the medullary canal and the intramedullary nail respectively. Inserting the nail first enabled to drill the locking bolt hole where the intramedullary nail will pass through and to drill in a perpendicular direction to the intramedullary nail. Instead of the centring drill guide a tissue protection sleeve was used (B).

be more difficult in clinical cases because of tissue contraction and swelling. In addition, we performed experimentally induced fractures to standardize the conditions of fracture repair. This might have simplified advancement of the nail compared with clinical cases with traumatic fractures. Although 23% of humeral fractures in cats affect the distal part of the bone,[38] the fracture gaps were created at the mid-diaphysis of all the bones to obtain consistency between the groups. Finally, the method of measurement for rotational alignment was not very precise, since the smallest unit on the used scale was 0.5 mm. However, these measurements were useful to identify if there was a trend toward rotational malalignment and for comparison between the groups. Besides these limitations the nature of this experimental study allowed to compare homogenous groups and to perform a standardized procedure with controlled variables, a critical advantage compared with clinical studies.

Finally, it should be emphasized that this feasibility study did not consider the mechanical performance of TVS in the postoperative period. A recent study concluded that TVS has a mechanical disadvantage in torsional stability, which might affect outcomes.[22]

We conclude that percutaneous TVS application can be safely performed in cadaveric cats without fluoroscopic guidance for stabilization of tibial fractures. We noticed an increased risk of intraoperative fractures in femoral application of the TVS, which can be reduced following specific surgical recommendations. Fluoroscopy, although not found to be essential, was beneficial especially during the learning phase and when complications occurred with the TVS. Despite the limitations of a cadaveric study, the high number of complications and postoperative neurovascular damage is leading us to consider the humerus to be unsafe for the TVS. A learning curve has to be expected and surgical recommendations should be respected to decrease these complications. In contrast to what was previously reported, we would recommend considering a minimal medullary bone diameter of 4 mm at location of the locking bolts in the frontal plane instead of the previously reported outer bone diameter of 8.5 mm.

Author Contribution

Katrin Nabholz contributed to conception of study, acquisition of data, and data analysis and interpretation. Antonio Pozzi contributed to conception of study and study design. Philipp A. Schmierer contributed to study design. Lucas A. Smolders contributed to data analysis and interpretation. Sebastian C. Knell contributed to conception of study, study design, and data analysis and interpretation. All authors drafted, revised and approved the submitted manuscript.

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Conflict of Interest

One (SCK) of the co-authors is a part time consultant for B. Braun Vet Care. The corresponding author has been working as a part time consultant for Aesculap B BRaun. AG, Tuttlingen, Germany.

References

1 Reems MR, Beale BS, Hulse DA. Use of a plate-rod construct and principles of biological osteosynthesis for repair of diaphyseal fractures in dogs and cats: 47 cases (1994-2001). J Am Vet Med Assoc 2003;223(03):330–335

2 Bennour EM, Abushhiwa MA, Ben Ali L, Sawesi OK, Marzok MA, Abuargob OM, et al. A retrospective study on appendicular fractures in dogs and cats in Tripoli – Libya. J Vet Adv 2014; 4 (03):425–431

3 Tobias KM, Johnston SA. Veterinary Surgery: Small Animal: 2-Volume Set. Elsevier Health Sciences; 2013:576–627

4 Palmer RH. Biological osteosynthesis. Vet Clin North Am Small Anim Pract 1999;29(05):1171–1185, vii

5 Pozzi A, Lewis D. Surgical approaches for minimally invasive plate osteosynthesis in dogs. Vet Comp Orthop Traumatol 2009;22(04): 316–320

6 Hudson CC, Pozzi A, Lewis DD. Minimally invasive plate osteosynthesis: applications and techniques in dogs and cats. Vet Comp Orthop Traumatol 2009;22(03):175–182

7 Schmierer PA, Pozzi A. Guidelines for surgical approaches for minimally invasive plate osteosynthesis in cats. Vet Comp Orthop Traumatol 2017;30(04):272–278

8 Nolte DM, Fusco JV, Peterson ME. Incidence of and predisposing factors for nonunion of fractures involving the appendicular skeleton in cats: 18 cases (1998-2002). J Am Vet Med Assoc 2005;226(01):77–82

9 McCartney WT, MacDonald BJ. Incidence of non-union in long bone fractures in 233 cats. Int J Appl Res Vet Med 2006;4(03):209–212

10 Horstman CL, Beale BS, Conzemius MG, Evans R R. Biological osteosynthesis versus traditional anatomic reconstruction of 20 long-bone fractures using an interlocking nail: 1994-2001. Vet Surg 2004;33(03):232–237

11 von Pfeil DJF, Déjardin LM, DeCamp CE, et al. In vitro biomechanical comparison of a plate-rod combination-construct and an interlocking nail-construct for experimentally induced gap fractures in canine tibiae. Am J Vet Res 2005;66(09):1536–1543

12 Déjardin LM, Guiot LP, von Pfeil DJ. Interlocking nails and minimally invasive osteosynthesis. Vet Clin North Am - Small Anim Pract 2012; 42(05):935–962

13 Lansdowne JL, Sinnott MT, Déjardin LM, Ting D, Haut RC. In vitro mechanical comparison of screwed, bolted, and novel interlocking nail systems to buttress plate fixation in torsion and mediolateral bending. Vet Surg 2007;36(04):368–377

14 Déjardin LM, Guillou RP, Ting D, Sinnott MT, Meyer E, Haut RC. Effect of bending direction on the mechanical behaviour of interlocking nail systems. Vet Comp Orthop Traumatol 1995;8 (03):146–152

15 Muir P, Johnson KA, Markel MD. Area moment of inertia for comparison of implant cross-sectional geometry and bending stiffness. Vet Comp Orthop Traumatol 1995; ((03):24–30

16 Duhautois B. Use of veterinary interlocking nails for diaphyseal fractures in dogs and cats: 121 cases. Vet Surg 2003;32(01):8–20

17 Dueland RT, Johnson KA, Roe SC, Engen MH, Lesser AS. Interlocking nail treatment of diaphyseal long-bone fractures in dogs. J Am Vet Med Assoc 1999;214(01):59–66

18 Moses PA, Lewis DD, Lanz OI, Stubbs WP, Cross AR, Smith KR. Intramedullary interlocking nail stabilisation of 21 humeral fractures in 19 dogs and one cat. Aust Vet J 2002;80(06):336–343

19 Díaz-Bertrana MC, Durall I, Puchol JL, Sánchez A, Franch J. Interlocking nail treatment of long-bone fractures in cats: 33 cases (1995-2004). Vet Comp Orthop Traumatol 2005;18(03): 119–126

20 Basinger RR, Suber JT. Two techniques for supplementing interlocking nail repair of fractures of the humerus, femur, and tibia: results in 12 dogs and cats. Vet Surg 2004;33(06):673–680

21 Brückner M, Unger M, Spies M. In vitro biomechanical comparison of a newly designed interlocking nail system to a standard DCP. Testing of cat femora in an osteotomy gap model. Tierarztl Prax Ausg K Klientiere Heimtiere 2014;42(02):79–87

22 Macedo AS, Moens NMM, Runciman J, Gibson TW, Minto BW. Ex vivo torsional properties of a 2.5 mm veterinary interlocking nail system in canine femurs. Comparison with a 2.4 mm limited contact bone plate. Vet Comp Orthop Traumatol 2017;30(02):118–124

23 Brückner M, Unger M, Spies M. Early clinical experience with a newly designed interlocking nail system-Targon(®) Vet. Vet Surg 2016;45(06):754–763

24 Jaarsma RL, van Kampen A. Rotational malalignment after fractures of the femur. J Bone Joint Surg Br 2004;86(08):1100–1104

25 Guiot LP, Déjardin LM. Perioperative imaging in minimally invasive osteosynthesis in small animals. Vet Clin North Am - Small Anim Pract 2012; 42(05):897–911.

26 Decamp CE. Brinker, Piermattei and Flo's Handbook of Small Animal Orthopedics and Fracture Repair. 5th ed. London: W.B. Saunders; 2015

27 Giachino AA, Cheng M. Irradiation of the surgeon during pinning of femoral fractures. J Bone Joint Surg Br 1980; 62–B(02): 227–229

28 Seals KF, Lee EW, Cagnon CH, Al-Hakim RA, Kee ST. Radiation-induced cataractogenesis: a critical literature review for the interventional radiologist. Cardiovasc Intervent Radiol 2016;39(02):151–160

29 Tremains MR, Georgiadis GM, Dennis MJ. Radiation exposure with use of the inverted-C-arm technique in upper-extremity surgery. J Bone Joint Surg Am 2001; 83–A((05):674–678

30 Swanson EA, Tomlinson JL, Dismukes DI, Fox DB. Measurement of femoral and tibial joint reference angles and pelvic limb alignment in cats. Vet Surg 2012;41(06):696–704

31 Wood MC, Fox DB, Tomlinson JL. Determination of the mechanical axis and joint orientation lines in the canine humerus: a radiographic cadaveric study. Vet Surg 2014;43(04):414–417

32 Boero Baroncelli A, Peirone B, Winter MD, Reese DJ, Pozzi A. Retrospective comparison between minimally invasive plate osteosynthesis and open plating for tibial fractures in dogs. Vet Comp Orthop Traumatol 2012;25(05):410–417

33 Langley-Hobbs SJ, Straw M. The feline humerus. An anatomical study with relevance to external skeletal fixator and intramedullary pin placement. Vet Comp Orthop Traumatol 2005;18(01):1–6

34 Scotti S, Klein A, Pink J, Hidalgo A, Moissonnier P, Fayolle P. Retrograde placement of a novel 3.5 mm titanium interlocking nail for supracondylar and diaphyseal femoral fractures in cats. Vet Comp Orthop Traumatol 2007;20(03):211–218

35 Rupp RE, Chrissos MG, Ebraheim NA. The risk of neurovascular injury with distal locking screws of humeral intramedullary nails. Orthopedics 1996;19(07):593–595

36 Baltov A, Mihail R, Dian E. Complications after interlocking intramedullary nailing of humeral shaft fractures. Injury 2014; 45(Suppl 1):S9–S15

37 Noger M, Berli MC, Fasel JHD, Hoffmeyer PJ. The risk of injury to neurovascular structures from distal locking screws of the Unreamed Humeral Nail (UHN): a cadaveric study. Injury 2007; 38(08):954–957

38 Bardet JF, Hohn RB, Rudy RL, Olmstead ML. Fractures of the humerus in dogs and cats a retrospective study of 130 cases. Vet Surg 1983;12(02):73–77